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Microwave Planar Sensor for Permittivity Determination of Dielectric Materials

Rammah Alahnomi[1], Natasha Binti Abd Hamid[2], Zahriladha Zakaria[3], Tole Sutikno[4], Amyrul Azuan Mohd Bahar[5]
[1,2,3,5]Centre for Telecommunication Research and Innovation (CeTRI), Universiti Teknikal Malaysia Melaka (UTeM), 76100, Durian Tunggal, Melaka, Malaysia.
[4]Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

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ABSTRACT

This paper presents a single port rectangular ring resonator sensor for material characterizations. The proposed sensor is designed at operating resonance frequency of 4 GHz. The sensor consists of micro-strip transmission line and ring resonator with applying the enhancement method to the coupling gaps. The using of enhancement method is to improve the return loss of the sensor and sensitivity in terms of Q-factor, respectively. Furthermore, the proposed sensor is designed and fabricated on Roger 5880 substrate. Standard materials with known permittivity have been used in order to validate the sensor's sensitivity. Based on the results, the percentage of error for the proposed rectangular sensor is 0.2% to 8%. It can be demonstrated that the proposed sensor will be useful for various applications such as medicine, bio-sensing and food industry.

Corresponding Author:

Zahriladha Zakaria
Centre for Telecommunication Research and Innovation (CeTRI),
Universiti Teknikal Malaysia Melaka (UTeM),
76100, Durian Tunggal, Melaka, Malaysia.
E-mail: zahriladha@utem.edu.my

1. INTRODUCTION

In recent years, material characterization techniques have been introduced. Many techniques are available to measure the real part of the complex permittivity or dielectric constant. In a material, there is the mixture of different size of molecules. Then, from the structure of molecule inside the material, the permittivity can be determined (1). The response of material to the electrical signal depends on the permittivity of the material. Generally, the accurate determination of the permittivity is an important task for microwave or radio frequency circuit design, antenna design and of course to the microwave engineering (2–5). Furthermore, the changes of dielectric properties of material or material characterization are widely used in many fields such as food industry, quality control, bio-sensing or medical industry (6–9).

Microwave measurement is an excellent sensing technique where it is used because of its non-invasive characteristics, ability of penetration sensing, real time and highly accurate detection methods. There are two types of methods that can be used to measure the dielectric through a microwave technique which are non-resonant and resonant methods. Resonant method acquire high accuracy compared to non-resonant method; the reason of choosing resonant method instead of non-resonant method. Then, through resonant method, the material under test (MUT) is introduced to the resonator; change the electromagnetic boundaries of the resonator. Instead of that, the electromagnetic properties of the sample being used are deducted because there is a change of resonant properties of the resonator. In other words, the resonant method is being used to gain the precise dielectric properties only at a single frequency or several discrete frequencies.

Meanwhile, the non-resonant method is used to get the electromagnetic properties of the material over a frequency range.

The resonator is usually applied as an accurate instrument for electromagnetic properties of a material like complex permittivity, permeability and the resistance for microwave frequencies compared to non-resonant. Furthermore, it is widely being used for low-loss, small size sample and also sample with irregular shape due to its high accuracy. The high quality factor (Q-factor) of the resonator cause a high sensitivity device where it can be used to sense the difference in physical quantities; depends on the complex permeability of MUT (10–14).

1.1. Perturbation Technique

The most popular technique for measuring the complex permittivity of lossy material is known as the perturbation technique. Perturbation technique has been used for many decades for measuring the electromagnetic characteristics between the empty and partially loaded MUTs (15). This technique is the most common used technique due to its simplicity and accuracy. When a small piece of dielectric material (MUT) is introduced into the resonant cavity, the resonance frequency is shifted by a small amount (16). Plus, the selectivity of the cavity is lowered. These effects are commonly used in the measurement of properties of the material; the relation between the shifted of resonance frequencies, selectivity and the permittivity of the sample. The MUTs is placed at a specific location on the resonator where the electric field (e-field) is at a maximum condition. Then, the insertion of the MUTs within the cavity causes the effect of perturbation to the overall circuit. The perturbation cause a shifting of the resonance frequency and a decrease in the unloaded Q-factor.

The response of the cavity in the perturbation is particularly related to the dielectric properties of the tested material through the cavity perturbation theory. Based on the theory of perturbation, it is anticipated that the fractional change in the resonant frequency has increased with the increasing of the dielectric constant of the MUTs (13,17,18). The resonance frequency is shifted to the lower frequency when the MUTs are being placed on the resonator sensor. This is because of the maximum electric field of the resonator sensor when it is perturbed to the sample. Besides, more fringing field is focused into the overlay sample. While, the other changes that can be seen when the sample is placed on the resonator sensor is the changes in dB level. The changes in dB level is due to the effective dielectric properties of the sample; the permittivity.

1.2. Reflection Method

Reflection methods is a method which able to measure only one of the parameters, either the permittivity or the permeability. In this project only the permittivity parameter is measured. The electromagnetic waves are directed to the MUT, then the properties of the sample can be detected from the reflection coefficient that occur in the defined reference plane. To apply the reflection method in the measurement of the dielectric property, one port resonator is mainly used. The single port capability to transmit the signal in one port, then, the received signal is reflected back from the MUT to the same port it transmits before. The measured S-parameter is S1,1 or S2,2. The dynamic range of reflection measurements is limited by the directivity of the measurement port.

The one port calibration is needed in order to improve the accuracy and sensitivity of the measurement of the system. Through the calibration, it can measure and remove the three systematic error terms in the measurement of the system; the directivity, source match and also the reflection tracking. But, in the standard cases, the high accuracy and sensitivity like "short" or "air" are not required. The simple calibration is enough to be conducted (17). In Figure 1, it shows the graph of S-parameter, S1,1. The value of the S1,1 can be determined by using the equation 1; for determining the half-power width. In the equation 1.1, the S1, 1b is the base line of the resonance for S1, 1 value. While, the S1, 1fo is the resonance frequency value for the S1,1 (19) . Besides, from Figure 1 also the Q-factor of the resonator can be determined based on the bandwidth and the resonant frequency.

$$S_{1,1\Delta f} = 10\log\left(\frac{10^{\frac{s1,1b}{10}} + 10^{\frac{s1,1f0}{10}}}{2}\right)(\mathrm{dB}) \tag{1}$$

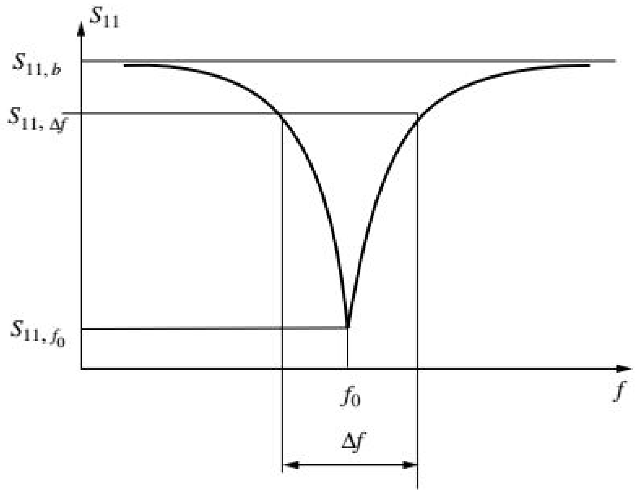

Figure 1. parameter for the reflection method

2. GEOMETRY DESIGN & MATHEMATICAL ANALYSIS

To design a micro-strip ring resonator, the principle that can be used to enable the changes of effective permittivity if any dielectric material is placed on the substrate surface; cause the changes in the resonant frequency. The resonant frequency is determined by using the equation of 'f' as shown in Equation 2.

$$\mathrm{f} = \frac{1}{2\pi\sqrt{\mathrm{LC}}} \quad (2)$$

While the inductance, L can be approximated by:

$$L = \mu_o R_m(\ln\frac{8R_m}{h+w} - 0.5) \quad (3)$$

R_m: main radius of the ring
h: Height of the substrate
w: The width of the feed-line

The capacitor, C can affect the resonant frequency and it can be determined by using below equation:

$$C = \frac{\varepsilon_{ro}\,\varepsilon_r A}{d} \quad (4)$$

A: Area of the gap
d: Distance of the gap
ε_r: Relative permittivity of dielectric presents between the plates

To calculate the feed-line dimension and coupling the following equations are used, where the feed-line width is:

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r + 1}{\varepsilon_r - 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (5)$$

$$\frac{w}{d} = \frac{8e^A}{e^{2A} - 2} \quad (6)$$

Where d is the thickness of the substrate.

$$Feedline\ length, \iota = \frac{\lambda g}{4} \quad (7)$$

$$\text{The coupling gap}, \lambda g = \frac{c}{f\sqrt{\varepsilon_{eff}}} \tag{8}$$

Where λg is the wavelength at the given frequency

$$\text{Eff. permittivity}, \varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1+\frac{12d}{w}}}\right) \tag{9}$$

$$\text{Coupling gap}, \Delta L = 0.421d\left(\frac{\varepsilon_{eff} + 0.3}{\varepsilon_{eff} - 0.258}\right)\left(\frac{\frac{w}{d} + 0.262}{\frac{w}{d} + 0.818}\right) \tag{10}$$

The micro - strip resonator sensor is a close-loop transmission line. To form the resonant frequency, the power is capacitive coupled through the feed-line and the gap between them. So, the resonant frequency happens when the mean circumstances of the ring are equal to the integral of the guided wavelength. $2\pi r = n\lambda g$ for n = 1 ,2 ,3…

$$\text{Frequency dependent}, \lambda g = \frac{\lambda}{\sqrt{\varepsilon_{eff}}} = \frac{1}{\sqrt{\varepsilon_{eff}}}\frac{c}{f} \tag{11}$$

$$f_o = \frac{nc}{2\pi r\sqrt{\varepsilon_{eff}}} \tag{12}$$

r: Ring radius
n: 1, 2, 3…
c: 3× 〖10〗^8 m/s (speed of light)
ε_{eff}: Effective permittivity of the substrate

Decreasing in gap cause the gap capacitance increases and make the coupling constricted. Then the increase in gap capacitance effect the resonator frequency; lower frequency. This circumstance is known as 'pushing effect'.

The effective permittivity regarding the resonant frequency, f_c:

$$\varepsilon_{eff} = \left(\frac{nc}{2\pi\, f_c r_m}\right)^2 \tag{13}$$

The ring radius:

$$\text{Outer radius}, R_o = r + \frac{w}{2} \tag{14}$$

$$\text{Inner radius}, R_i = r - \frac{w}{2} \tag{15}$$

$$\text{Quality factor}, Q = \frac{2f_c}{BW} \tag{16}$$

f_c: Resonant frequency
BW: Bandwidth of the resonant frequency

The length of substrate, *Lg* can be determined by:

$$\text{Length of substrate}, Lg = 2l + 2\Delta L + 2R_o \tag{17}$$

While, for the width of the substrate, Wg

$$\text{Width of substrate}, Wg = 2R_o + \frac{\lambda g}{4} \tag{18}$$

Through this project of microwave sensor, the numerical result will be used for circuit design in the CST software. The schematic diagram for the proposed rectangular design sensor is shown in Figure 2. The parameters being used are illustrated in Table 1.

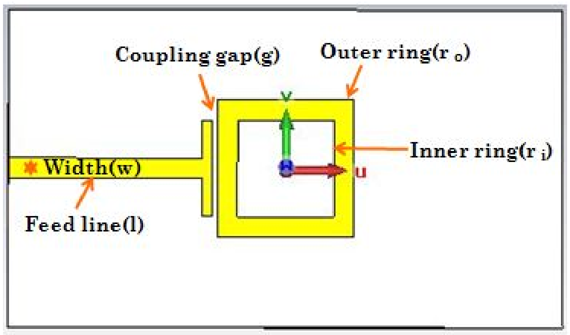

Figure 2. Schematic diagram of the proposed rectangular resonator sensor

Table 1. Parameters in designing the single port rectangular resonator sensor

Parameter	Design value
Substrate: Roger 5880	Frequency: 4GHz
Substrate thickness	0.787mm
Substrate permittivity, ε_r	2.2
Length of substrate (Lg)	68.12mm
Width of substrate (Wg)	38.69mm
Feed-line length (l)	25.35mm
Outer ring (ro)	8.4mm
Inner ring (ri)	5.9mm
Gap (g)	0.62mm
Width of feed-line (w)	2.5mm

3. RESULTS AND DISCUSSION

3.1. Simulated Result

The single port rectangular resonator sensor with the resonance frequency of 4 GHz is designed on CST software. The dimension of the structure of the resonator sensor is calculated based on the mathematical analysis. While, there are three parameters have been measured through the sensor like the resonant frequency, Q-factor and the return loss with five different samples and permittivity; air, Roger 5880, Roger 4350, FR-4 and Roger 3010.

The sensor is constructed by using the Roger 5880 with the thickness of 0.787 mm and loss tangent of 0.009. The basic rectangular resonator sensor is demonstrated in Figure 3. But, based on the S11 result, it shows that the sensor operates on 3.992 GHz and has a large return loss which is -6.4881 dB; the targeted return loss is less than -10 dB.

Although the basic resonator sensor able to shows a good performance in the resonant frequency and also in the strength of the electromagnetic field, the basic design needs a modification. Thus, a modification in the design is proposed in order to improve the return loss of the resonator sensor. The enhancement method is introduced in the design to overcome the problem of low performance in the resonator due to the large return loss. Figure 4 shows the structure of the rectangular sensor with the enhancement method.

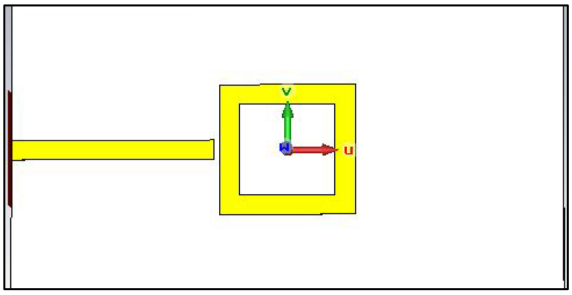

Figure 3. The basic rectangular resonator sensor.

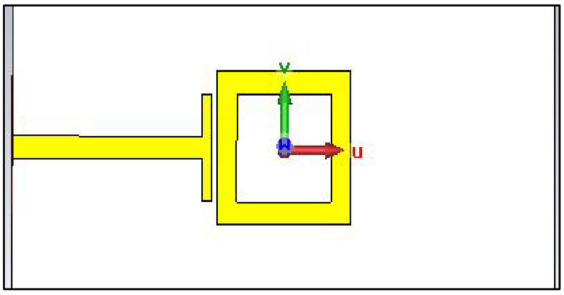

Figure 4. The structure of proposed resonator sensor.

The performance of the proposed resonator sensor with the enhancement method is measured based on the S11 signal due to the usage of the reflection method. The bandwidth of the S1, 1 is gathered at -3dB from the base line of the resonance of S11; refer to Figure 5. So, the resonance frequency is occurring at 3.992 GHz while the bandwidth of the S11 is 0.070678 GHz. The Q-factor of the proposed resonator sensor in the simulation is 113.

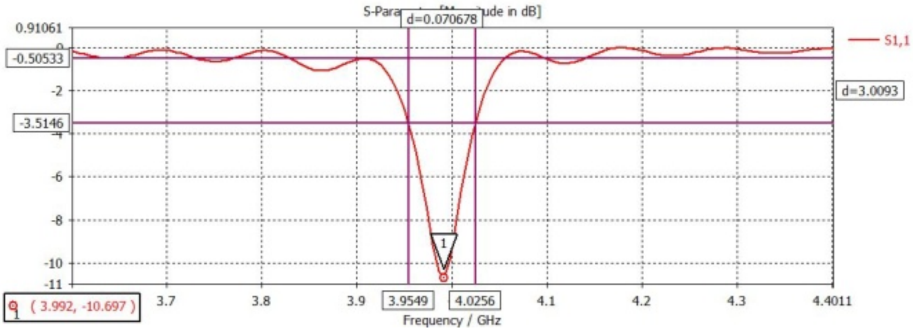

Figure 5. The S1,1 graph of the proposed design

The material under test (MUTs) are placed in a maximum electric field (e-field) region as indicated in Figure 6 and Figure 7. Thus, the resonator sensor produces a reduction in the Q-factor as well as the reduction in the resonant frequency as associated with the loss of the material. Then, the resonator sensor can be used to measure the dielectric properties of the MUTs by using the perturbation method; based on the shifting of the resonance frequency.

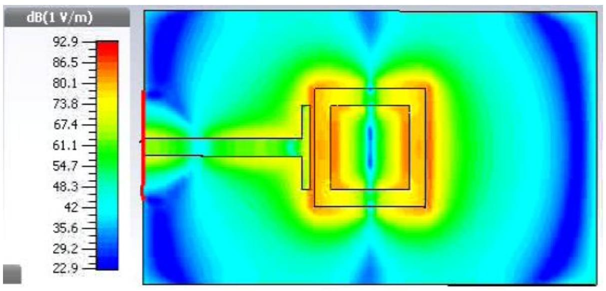

Figure 6. The e-Field in the Resonator Sensor

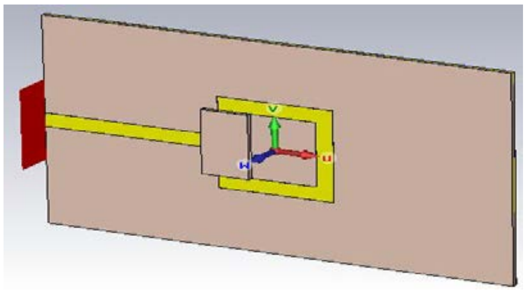

Figure 7. The Overlay Sample on the Resonator Sensor

In Figure 8, it shows the changes in the resonant frequency after different types of material is placed on the resonator sensor through simulation in CST software, the frequency is shifted. Four samples have been tested like FR-4, Roger 5880, Roger 4350 and Roger 3010. The resonant frequency with the sample of air refers to the without sample situation. Besides, based on Figure 8 also, it shows that the frequency is shifted to the lower frequency when the overlay sample is used. This situation happens because of the maximum electric field of the resonator when it is perturbed to the sample. Plus, more fringing fields are focused into the overlay sample. The return loss level (dB) also shows a variation when the sample is applied to the resonator sensor. This is due to the effective dielectric constant.

The bar chart in Figure 9 shows the graphical representation of the percentage frequency shifting for the resonant frequency. Based on both data representations, it shows that the sensitivity of the sensor can be represented in terms of relative shift in resonance frequency with the permittivity of MUTs. It is concluded that the higher the permittivity of the samples causes the higher the percentage of frequency shifting. Roger 5880 has the lowest percentage which is 2.6 %, followed by Roger 4350, 8.4 %, FR-4 16.8 % and Roger 3010, 27.6 %. Where the permittivity of Roger 5880 is 2.2, Roger 4350 is 3.48, FR-4 is 4.4 and Roger 3010 is 10.2.

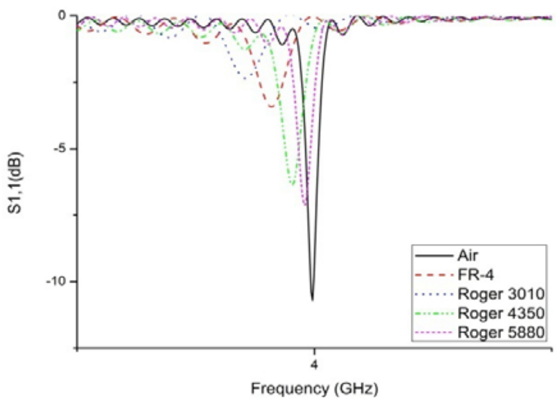

Figure 8. The Changes of Resonant Frequency with Different Overlay Samples in Simulation

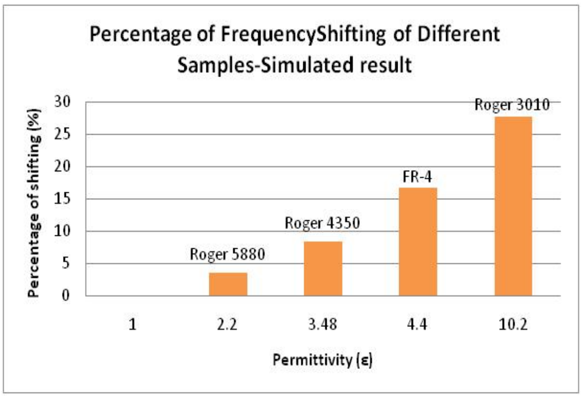

Figure 9. The Percentage of Frequency Shifting of Different MUTS

3.2. Measured Result

The proposed resonator sensor is fabricated on Roger 5880 substrate and it is found to be working on 3.98GHz of resonant frequency. Figure 10 shows the experimental setup for the fabricated sensor. The changes of resonant frequency and return loss of the MUTs are measured by using the vector Network Analyzer (VNA). The S11 data gained from the measurement is imported to the CST software. Based on the S11 result, it shows that the return loss is -6.3575dB and the Q-factor is 174. The improvement of the sensor in term of Q-factor is 54%.

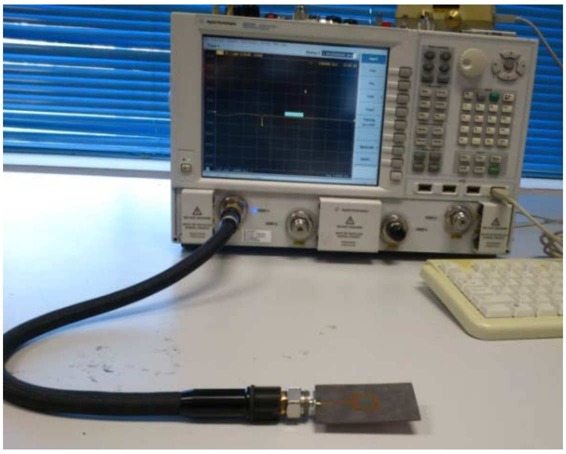

Figure 10. Experimental Setup of the Sensor.

While, Figure 11 shows the result of the measurement of different types of MUTs and permittivity. The data in Figure 11 is then represented in the bar chart; Figure 12. The measurement results show that the sample of Roger 3010 has the highest percentage of frequency shifting with an enormous difference of frequency when compared with the resonant frequency without shifting. The percentage of frequency shifting is 26.7%. The lowest percentage of frequency shifting happens with the sample Roger 5880, followed by Roger 4350 and FR-4. The measurement result also shows that the higher the permittivity of the sample, the larger the percentage of frequency shifting.

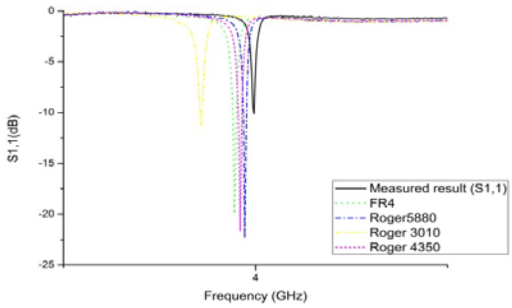

Figure 11. The Changes of Resonant Frequency with Different Overlay Samples in Simulation.

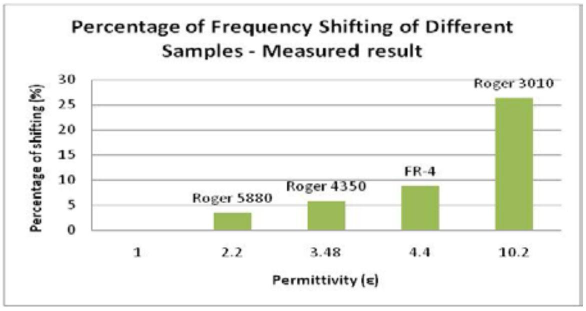

Figure 12. The Percentage of Frequency Shifting of Different MUTs.

Then, the simulation and measurement results of the sensor without sample (air) is demonstrated in Figure 13. There is a small deviation that occur between the simulated and measured results. The measured resonance frequency is slightly shifted from the simulation and the magnitude of the return loss is higher than the simulated results. This situation happens due to the mismatch between the feed-line and the connector of the port. Plus, it also happens because of the tolerance of fabrications which limits the simulation accuracy.

The result shown in Figure 13 illustrates that the performance of the fabricated resonator sensor is in a good agreement with the sensor in the simulation. By using the measured data, the relationship between the shifting of resonant frequency and the standard permittivity can be modeled by using the second order polynomial. It is the derivation of numerical model which is used to calculate the permittivity of the MUT. The derivation model applied the curve fitting method instead; refer to Figure 14. Then, the measured permittivity of the tested MUT is mathematically expressed as Equation 19.

$$\varepsilon_{r=} - 21.25f(x)^2 + 128.5f(x) - 173.9 \tag{19}$$

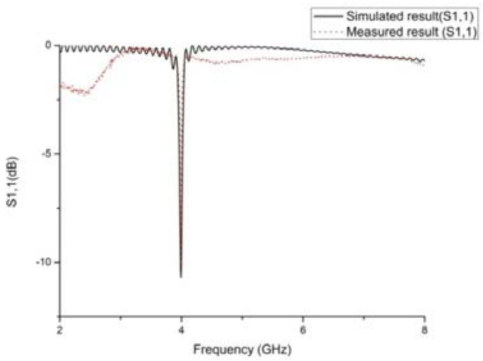

Figure 13. Comparison between Simulated and Measured Results based on the S11.

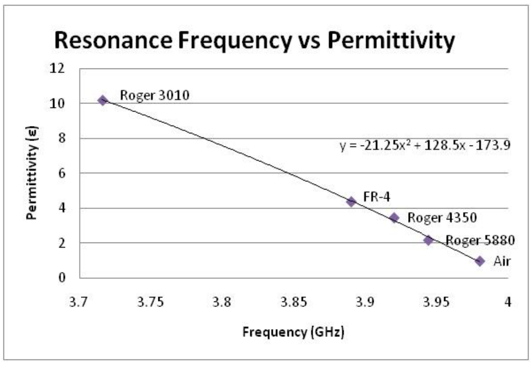

Figure 14 The Relationship between the Resonant Frequency and Permittivity.

From Table 2, it shows the result of the calculated permittivity. The error of the permittivity regarding the usage of Equation 19 is in the range of 0.2% to 8%. The higher the permittivity of the sample, the lower the error.

Table 2. The Calculated Permittivity based on Equation 19

MUTs	Frequency (GHz)	Permittivity, ε_r	Calculated ε_r	Error (%)
Air	3.98	1	0.9215	7.85
Roger 5880	3.944	2.2	2.3574	7.15
Roger 4350	3.92	3.48	3.284	5.63
FR-4	3.89	4.4	4.41	0.23
Roger 3010	3.716	10.2	10.17	0.29

4. COMPARED WITH EXISTING RESONATOR SENSOR

Two journals have been discussed about the resonator sensor which are being used for dielectric characterization of MUTs based on the permittivity are compared to the proposed sensor. Both of the journals proposed the same idea of design for the resonator sensor; based on the complementary split ring resonator (CSRR) structure. Only the shape of the design is different; one is circular while the other is rectangular. Each design has its own advantage and disadvantages.

Table 3 shows the tabulated data which have been compared with the proposed resonator sensor. The comparison is made based on the resonance frequency, Q-factor and the return loss. From the table, it shows that the proposed resonator sensor has the highest Q-factor compared to other two designs. But, the return lost of the proposed sensor is the lowest. The result of the proposed sensor is due to the usage of the enhancement method in the design where it introduces the "pushing effect" on the sensor. The method being used by the M Arif Hussain et [17] shows the opposite result compared to the proposed rectangular sensor where the sensor has a very low Q-factor, ≈64 but the return loss can achieved until -22.34dB. Then, each of the methods has a different level of resonance frequency.

Table 3. Comparison between Different Techniques with the Proposed Sensor (20,21)

Method	Specifications		
	Frequency (GHz)	Q-factor	S2,1/S1,1 (dB)
[17]	2.65	80	-21.00
[18]	1.28	≈64	-22.34
Proposed sensor	3.98	174	-6.3575

The percentage of error is calculated in order to measure the accuracy of the proposed rectangular sensor. The data is represented in Table 4. Through the tabulated data, it shows that the proposed sensor gains the lower range of error compared to the existing sensor. The percentage of error in the permittivity for the proposed sensor is 0.29% to 7.85%, while for the existing sensor, the percentage of the error in the permittivity is 0.57% to 12.70% instead.

Table 4. Measurement Accuracy of the Proposed Sensor in Comparison with the Existing Resonator Sensor (20,22–24)

MUTs	Std. permittivity, ε_r	Existing sensor		Proposed sensor	
		ε_r	% of error	ε_r	% of error
Air	1	1.08	8.0	0.9215	7.85
Roger 5880	2.2	1.92	12.70	2.3574	7.15
Roger 4350	3.48	3.5	0.57	3.284	5.63
FR-4	4.4	4.15	5.68	4.41	0.23
Roger 3010	10.2	-	-	10.17	0.29

While analyzing Table 4, it shows that the percentage of error in the proposed sensor is decreased linearly. The higher the permittivity of the MUTs, the lower the percentage of error in the rectangular sensor. But, for the existing sensor, the data are taken from various sources. Thus, it cannot be analyzed based on the linearity of the error. But, in the existing sensor, the higher error is gained when there is Roger 5880 that act as the sample while the lowest error is gained when the Roger 4350 acts as the sample. When there is no sample overlay on the sensor, the error is 8%. For the FR-4 sample, the error of the permittivity is 5.68%.

5. CONCLUSION

The rectangular resonator sensor with the enhancement method is proposed in this paper. The proposed design of the resonator sensor is able to improve the return loss of the basic rectangular resonator sensor; less than -10dB. Regarding the simulated result, it shows that the performance of the proposed sensor is in good agreement with the calculated result. While, by measuring the permittivity of the known samples, it is found that the percentage of error for the proposed sensor is from 0.2% to 8%. The sensitivity and accuracy of the sensor has been analyzed in terms of Q-factor and return loss. In addition, it is noted that the shifting of the resonance frequency is affected by the permittivity of the sample. The higher the permittivity of the samples, the lower the resonance frequency. Thus, the fabricated resonator sensor is suitable to be applied in the real life like in the food industry, agriculture and so on.

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